VSB TECHNICAL UNIVERSITY OF OSTRAVA | FACULTY OF MATERIALS SCIENCE AND TECHNOLOGY

DIPLOMA THESIS

Factors Affecting Fracture Toughness of R7T Steel

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Description:

Investigating microstructure and mechanical properties of R7T steel for railway wheel. Production the most important factors affecting fracture toughness will be specified. Analyzing up to now obtained knowledge from literature: the effect of carbon content, heat treatment, micro-alloying, microstructural parameters on the mechanical properties. This will be used in experimental analysis conducted in labs. Actual experimental results will be compared with literature findings.

References:

HAHN, G.T. Influence of microstructure on brittle fracture toughness. Metallurgical Transactions A, 1984, 15A(6), pp. 947-959.
BROCK, D. Elementary Engineering Fracture Mechanics. Hague: Martinus Nijheff Pub., 1983.
ANDERSON, T.L. Fracture Mechanics, Fundamentals and Applications. New York: CRC Press, 1994, pp. 243.
Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

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Abstract

Fracture toughness is an important material property that resists the complete fracture or extends the subject's life even after the presence of defects or after initialization of failure or fracture. So, because of that, how affects the mechanical properties and factors to the fracture toughness is essential. R7T steel is substantial steel that is mainly used for the railway wheel and other applications.

We used Linear-elastic plane-strain fracture toughness K_{Ic} of Metallic materials method with compact tension specimen to relate the effect of mechanical properties and other factors. With the help of linear-elastic plane-strain fracture toughness K_{Ic} of Metallic materials method and microstructure evolution. We relate the microstructure and mechanical properties like yield strength, Ultimate tensile strength with fracture toughness.

The results indicate that yield strength and tensile strength are effects thoroughly fracture toughness. Moreover, microstructure also important because R7T steel is a family of medium carbon steel.

KEYWORDS: Fracture toughness, R7T steel, Mechanical properties, Pearlite, Railway wheel.

Abstrakt

Lomová houževnatost je důležitá vlastnost materiálu, která je mírou jeho rezistence úplné desintegrace, anebo mírou prodloužení životnosti konstrukční části, i když obsahuje defekty jako projev iniciace selhání. Proto znalosti, jakým způsobem mechanické vlastnosti a jiné faktory ovlivňují lomovou houževnatost, jsou zcela zásadní. Ocel R7T je ocel širokého použití, zejména však pro výrobu železničních kol a pro podobné aplikace. Pro hodnocení jsme využili výsledků lineárně-elastické lomové houževnatosti K_{Ic} testované za podmínek rovinné deformace. Testy byly provedeny na CT tělesech vhodných pro studium relace s dalšími mechanickými vlastnostmi, mikrostrukturou a jinými faktory, které tuto vlastnost ovlivňují. Zejména jsme studovali relaci mikrostruktury oceli, mechanických vlastností jako je mez kluzu nebo mez pevnosti a testované lomové houževnatosti. Výsledky ukazují, že mez kluzu a mez pevnosti jednoznačně souvisejí s lomovou houževnatostí. Kromě toho, lomová houževnatost je citlivá na mikrostrukturní stav oceli R7T, stejně jako tomu je u středně uhlíkových ocelí.

Klíčová slova:

Lomová houževnatost, ocel R7T, mechanické vlastnosti, perlit, železniční kolo

Contents

List of Figures

List of Tables

1.Introductions

1.1 Background

The most important aspect of railway operations is the interaction between rail and wheel. The patch of contact is tiny between them; at the same time, there are several loads and thermal loads also. Railway wheels have to encounter wear and damage while accelerating curving, slippage. While such activities, thermal stresses are produced in the contact reason of revolutions and their microstructure changes. The microstructure becomes an anisotropic microstructure; due to that, the degradation of mechanical properties occurs. As per development with respect to time, the demand for railway improvisation increases the speed and load because of that railway.

1.2 Railway wheel production

Medium carbon steel is 0.5 Wt. % Carbon used to manufacture the wheel due to its high strength and good wear properties. The fine grain of steel with fine lamellar Pearlite with ferrite microstructure provides an optimal compromise mechanical properties, wear-resistance and Thermal stability. Because of its ferrite- Pearlite steels predominately use. In Europe, the EN13262 material series primarily uses for wheel and rails production, which are medium carbon steel. ER7 is a member of EN13262, mainly used to produce freight rails because of rim quenching heat special treatment known as R7T steel [1].

The railway wheel production is mass production; however, supervision is vital because of its importance in safety and reliability. The railway wheel has four mainframes: hub, centre, rim, and flange. Each frame has a different function, and they should fulfil the requirements. For example, tensile strength should be 780-1050 MPa, Impact toughness greater than or equal to 95 for U notch. Residual stress should be there in the rim. The Strength at the centre should be less than in the rim. So, they required distant and controlling heat treatments concerning the needed properties.

Heat Treatment

1) Rim quenching - After austenitization about temperature 900 °C cooled the rim of the wheel to 300 °C with the help of water spray.

2) The temperature of the centre and hub of wheels near the transformation temperature. Further cooling takes place in the air.

3)The final annealing step at 500 °C to stress relief treatment without significant change in the microstructure.

1.3 Reliability and Comfort

The primary purpose of rim quenching is reliability and comfort. We will get homogeneity of microstructure in radial and circumferential directions in a rim. That provides good strength, produce the residual stresses in the rim, which helps to arrest the crack initiation and growth of the crack at surfaces. It increases the fatigue life of the wheel. A simple railway wheel with a radius of 920 mm and 10^7 gives about 30,000 Km service. Produced residual compressive stresses in a rim. The wheel's homogeneity microstructure gives uniform wear characteristics in the wheel tread. As a result of it prevents the wheel's unwanted deformation. It prevents the formation of flat and un-roundness of wheel and assures comfort-ness.

Breaking and slippage are vital things, which are causes of producing large amounts of thermal loads. The period of braking operation is long, result in prolonged heating of tread and rim. Thermal loading can initiate not only cracks in the rim but also increase the growth rate of crack. On the other hand, it reverses the residual stresses in the rim. At this time, fracture toughness plays a vital role. Fracture toughness is an essential property of a material that resists crack growth and increases the component's fatigue life. So, it is vital to find which and how factors affect the Fracture toughness of R7T steel [2].

2. Mechanical properties and test of railway wheel

While Performing the Test, the wheel should be formed by the same process and by the same forged method; it will be easy to relate the properties correctly. Railway wheel production is mass production, so they are produced in batch as required. The railway wheel is a sensitive part of the railway, so it should pass through various testing.

2.1 Tensile test

The tensile test is one of the essential mechanical tests which provide information about the following parameters:

1) Yield strength

2) Ductility

3) Ultimate tensile strength

4) Failure strength

5) Stress and strain relationship

Test method – The most important of two sections of the wheel is Rim and Web. Selection for a specimen from the wheel as per figure no.1

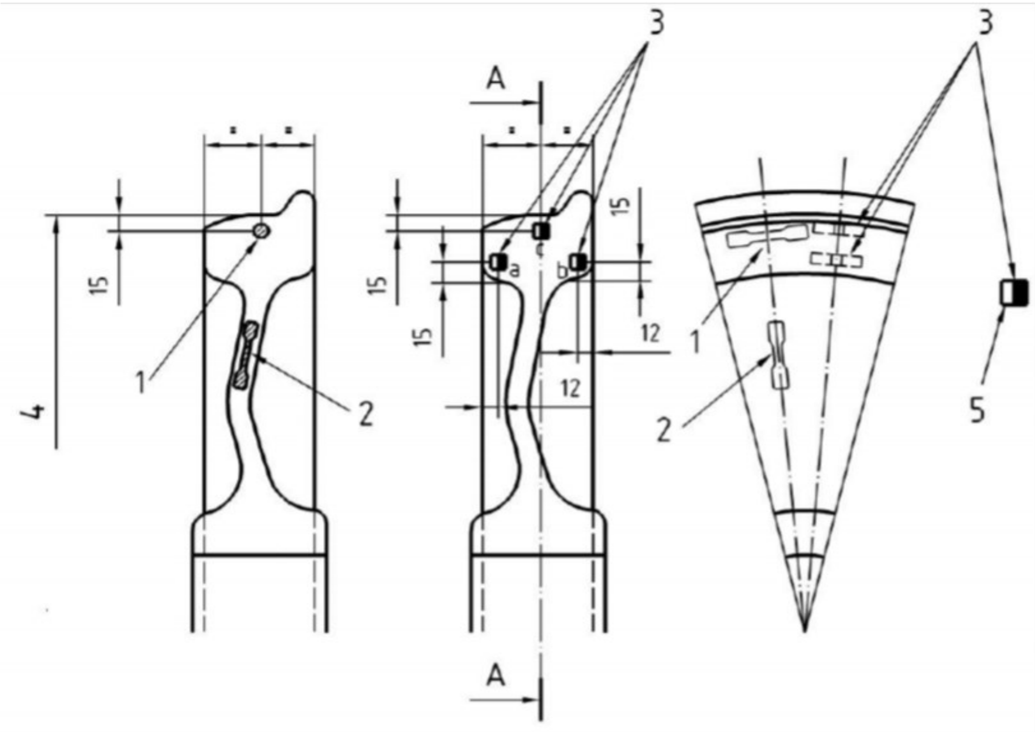


Figure 1. Location of specimen for testing in the wheel [3].

1- Specimen for Tensile test from rim portion below 15 mm from the tread and the mean diameter.

2 - Specimen for test for the web portion of the wheel.

3 - Impact test specimen.

4 - Nominal diameter of the wheel.

Tensile test carrying as ISO 6892-1 method B is stress rate based at the room temperature.

Results as per the standard from the European standard committee prEn13262.

R_{eh} - is the upper yield strength

R_m - is Tensile strength

A_s - is elongation

Table 1. ER7 Steel mechanical properties by test [3].

	Rim			Web	
Steel grade	R_{eh} (N/mm^2)	Rm (N/mm^2)	A_s %	R_m	A_s %
ER7	≥500	820/940	≥14	≥ 100	≥16

2.2 Hardness test

Hardness is an essential property of wheel material. With the help of hardness, we can observe the changes of phases with respect to sections of the wheel. When the wheel has sufficient hardness, it minimizes the wear rate. After 5,000 cycles, the wheels' wear rate rose with the more rigid rails, but after 15,000 was lower. The wheel material was work hardening which was affecting the wear rate [4].

Hardness Test

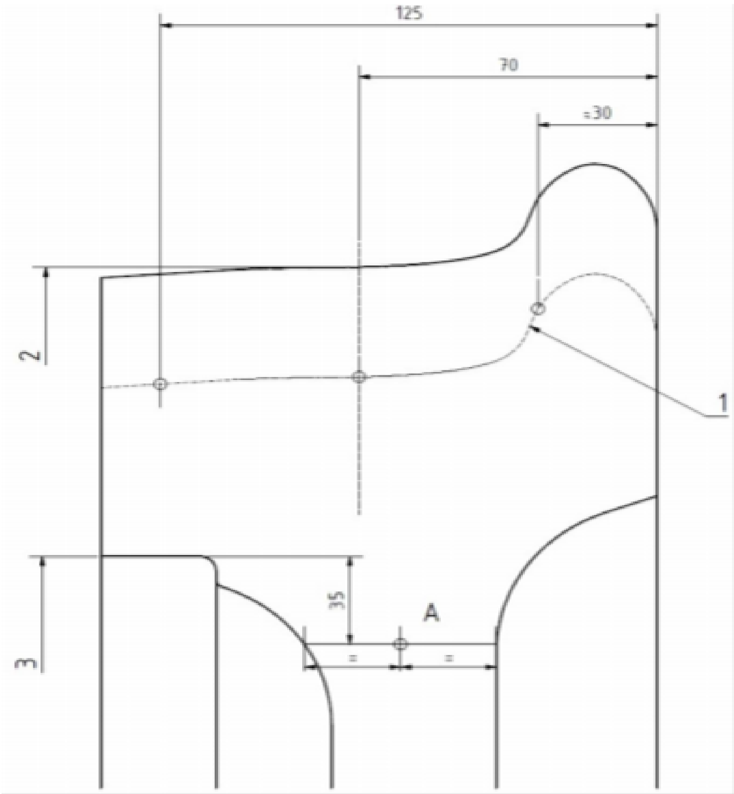


Figure 2. Hardness measurement sites as per standard [5].

In railway hardness test shall be performed in accordance with EN ISO 6506-1. The ball diameter is 5 mm.

.

Table 2. Hardness in Brinell hardness value

Steel	Category 1	Category 2
ER7	245	235

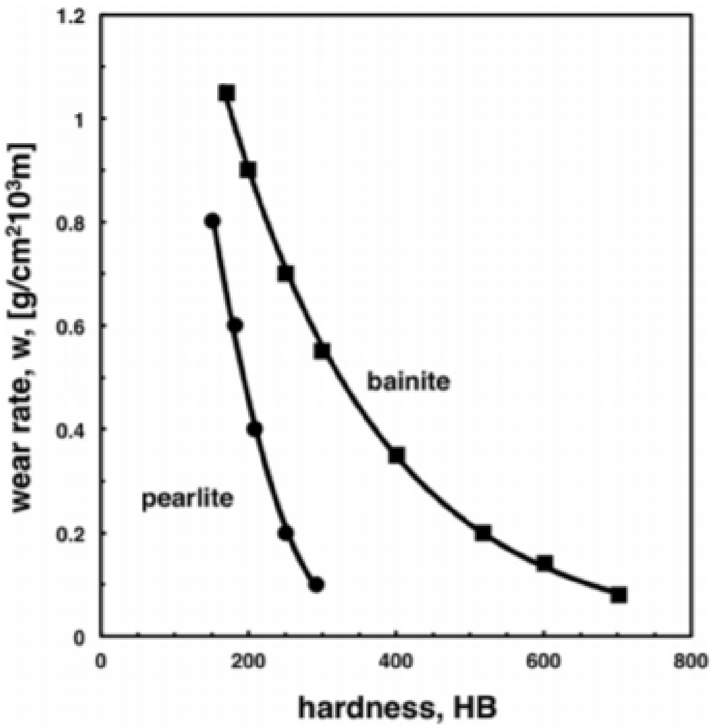


Figure 3. The hardness vs wear rate for R7T steel [6].

Hardness s an essential factor in the rail wheel, and it does not only oppose the deformation but also minimize the wear rate at the point of contact of the rail. A very important point is the presence of bainite at the rim's surface because of the heat-treatment conditions. However, there are good reasons to have no bainite in awheel rim made of ER7 steel. One is the reduced wear behaviour [6].

2.3 Mechanical properties and fracture toughness

Impact Energy and Fracture toughness

Impact toughness (Impact energy) is the essential mechanical property that gives the potential for fracture, plane strain fracture, and impact test to determine the material's fracture properties. In the CT test and Charpy V-notch test has different cleavage fracture. For example, in a CT specimen, the cleavage fracture initiates with multiple small cleavages, and in the CVN test, the cleavage fracture begins at the notch and/or ductile tip of the crack.

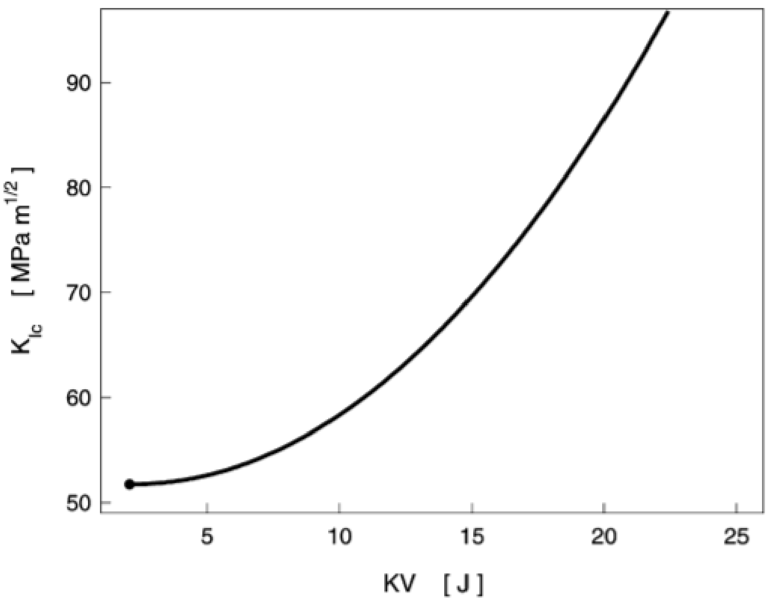


Figure 4. The relation between impact toughness and fracture toughness at ambient temperature [7].

The relation between the impact energy and fracture toughness can be related as they are directly proportional to each other. However, while increasing impact energy CVN) in the first region, the fracture toughness grows slowly. In the following region, the fracture toughness increases gradually with respect to the impact energy [7].

2.4 Ductile Brittle Transition Temperature

It is the temperature where ductile material becomes brittle and vice versa and shows changes in impact energy. Mostly low strength steel with a Body Centre Cubic crystal structure is sensitive to the DBT phenomenon.

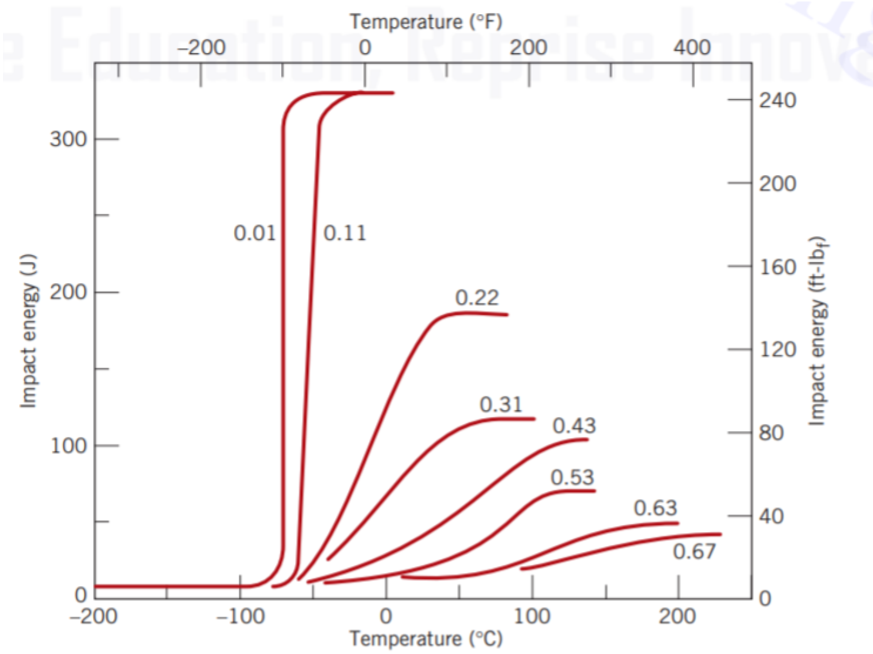


Figure 5. Impact energy and DBTT behaviour of steel with carbon percentage [8].

Increasing the carbon content in low-strengthening steel improves the Strength, but it increases the Ductile brittle Transition Temperature and decreases the impact energy. So, it will affect Fracture toughness, too [8].

2.5 Yield strength

Yield strength increases concerning temperature decrease while fracture toughness decreases. In low alloy steels, after the nil ductility temperature, the fracture toughness increases. After the nil ductility temperature, the material's ductility improved because crack propagation required more energy, which means its fracture toughness improved; however, the required properties are for the rail wheel are strength and good wear resistance [8].

3. Theoretical Part

3.1 Stress intensity factor K

The stress-intensity factor K is a parameter that quantifies the state of stress near the crack-tip in a linear elastic material. Equation 3.1 to 3.3 describes the stress at the crack tip in Mode I loading for the coordinate system shown in Figure 6.

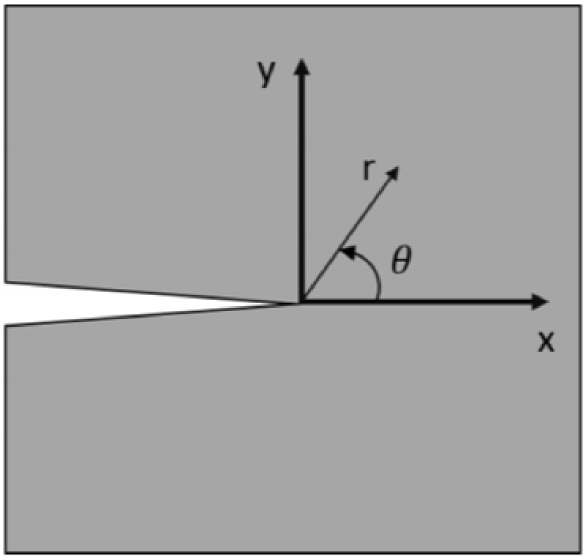


Figure 6. Coordinate system to calculate stress [8].

$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\left[1 - \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] \qquad \ldots(3.1)$$

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\left[1 + \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] \qquad \ldots(3.2)$$

$$\sigma_{zz} = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right) \qquad \ldots(3.3)$$

In plane stress

$$\sigma_{zz} = 0 \qquad \ldots(3.4)$$

In plane strain

$$\sigma_{zz} = v(\sigma_{xx} + \sigma_{yy}) \qquad \ldots(3.5)$$

3.2 K_{IC}

It has been found that materials fail at a critical magnitude of K, called the critical stress intensity or fracture toughness, KIC. The fracture toughness of a material is dependent on temperature, corrosive environment, boundary effects [9].

The fracture criterion can be stated as,

$$K_I > K_{IC}$$

As K describes the linear elastic stress intensity, it cannot fully describe the crack tip stress state at excessive yielding. In order to describe the crack tip state at excessive yielding, the J-integral can be used.

3.3 Plastic zone

Due to the theoretical infinite elastic stresses at the crack tip, it was yielding results in a plastic zone. Irwin estimated the plastic zone to have the size.

$$r_y = \frac{1}{2\pi}\left(\frac{k_I}{\sigma_{ys}}\right)^2 \qquad \ldots(3.5)$$

As the stresses are redistributed when the zone starts yielding, a more accurate plastic zone estimation of the size is.

$$r_p = 2r_y = \frac{1}{2\pi}\left(\frac{k_I}{\sigma_{ys}}\right)^2 \qquad \ldots(3.6)$$

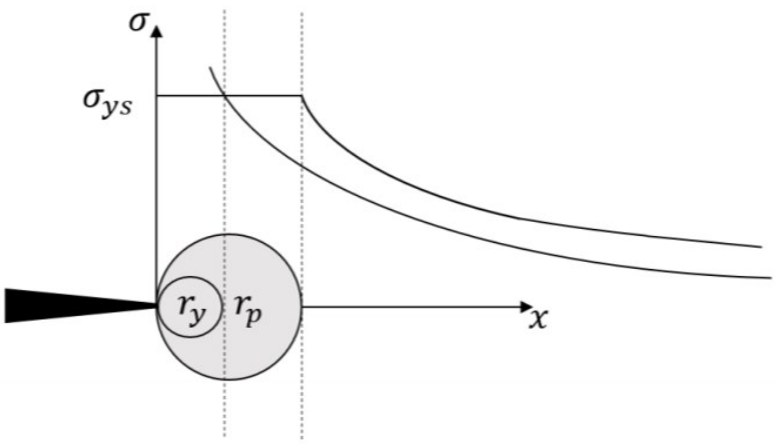


Figure 7. Plasticity at the crack tip [9].

Note that this is a simplification under plane-stress conditions. The plastic zone under plane-strain conditions is negligible. Dowling explains that LEFM is generally applicable if the crack size and the distance from the crack tip to a free edge are larger than 8ry; therefore, a ligament size requirement can be explained by equation no 3.7 [9].

$$a, (w - a), h > 8ry = \frac{8}{2\pi}\left(\frac{k_I}{\sigma_{ys}}\right)^2 = 1.27\left(\frac{k_I}{\sigma_{ys}}\right)^2 \quad \ldots(3.7)$$

3.4 Fracture test method

Fracture toughness is an essential property of a material. Fracture toughness is nothing but critical stress intensity where crack starts to propagate and initiate. The following two conditions should be satisfied to identify the stress intensity factor critical value as fracture toughness parameter of material [10].

The test performed according to EN ISO 12737.

For the test, the conditions are as follows:

- Compact tensile test pieces: 30 mm thick (CT 30), with chevron notch with an aperture angle of 90°.
- The temperature during the test to be between +15 °C and +25 °C.
- Measurement of the crack displacement of the test piece.
- The rate of increase of stress intensity ΔK/σ should be within the range from 0.55 N/mm2 √m/s to 1 N/mm2 √m/s.
- The toughness value to be considered is the value K_Q which is calculated from the load F_Q
- Value from the load-displacement record.

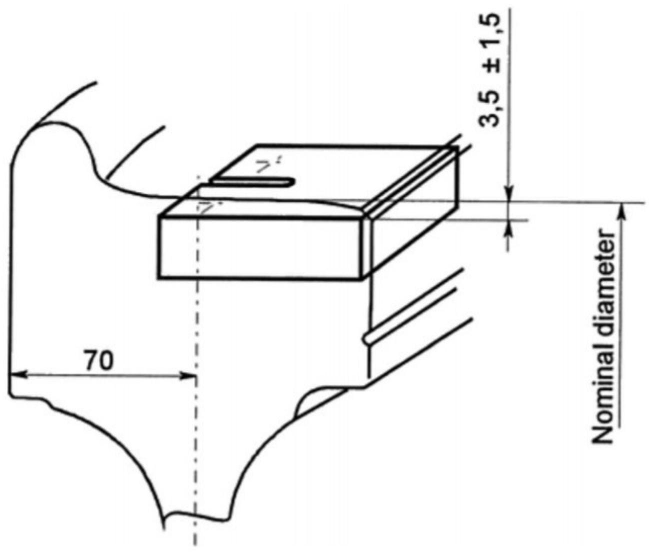


Figure 8. Selection of specimen for fracture toughness from railway wheel [10].

1)

$$B,\ a \geq \left(\frac{K_Q}{R_{p0.2}}\right)^2$$

B = thickness of sample

a = Crack length

$R_{p0.2}$ = Yield strength

2)

$$\left(\frac{\text{Pmax}}{\text{PQ}}\right) \geq 1.1\ \ P_{Q\ \text{Applied}}\ \text{load}$$

Fracture toughness is affected by the following objects.

1) Microstructure properties

2) Grain size

3) Chemical Composition (Carbon, Manganese)

4) Mechanical properties

5) Temperature

6) Specimen geometry

3.5 Material

For railway wheel required the following properties

1) High toughness to avoid brittle fracture

2) Sufficient strength to resist the plastic deformation

3) Thermal stability

4) Sufficient strength to resist wear

Eutectoid steels provide excellent toughness, but on the other hand, they provide insufficient toughness properties. We can improve the toughness too with the change grin size; however, the Hypo-eutectoid steel proved suitable toughness property at the same grain size. So, hypo eutectoid steel gives not only sufficient Strength but also good toughness property. Because of this property, medium carbon steel used for the railway wheel. R7T is also the family member of medium carbon property [6].

Modern materials for wheelsets made from vacuum degassed steels with accurate controlled chemical composition to minimize hydrogen content and formation of inclusions [11].

3.5.1 Chemical composition of R7T steel

Table 3. Alloy elements in the R7T steel.[4]

Elements	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V	Cr+ Mo+Ni
Wt.%	0.52	0.40	0.80	0.020	0.015	0.30	0.30	0.08	0.30	0.06	0.50

3.5.2 Alloy elements effects

Carbon and Manganese on fracture toughness

In the rim of the railway wheel, hardness and strength are required for good wear resistance. Carbon and Manganese are the essential second particles in R7T steel. Carbon and Manganese.

1) Manganese not only cleaning the iron by removing unwanted elements like sulphur and phosphorus. It helps to convert iron to steel. Manganese increases the hardenability of steel and helps Carbon. Increasing the manganese increase the hardness, but on the other hand, it affects the fracture toughness negatively [12].

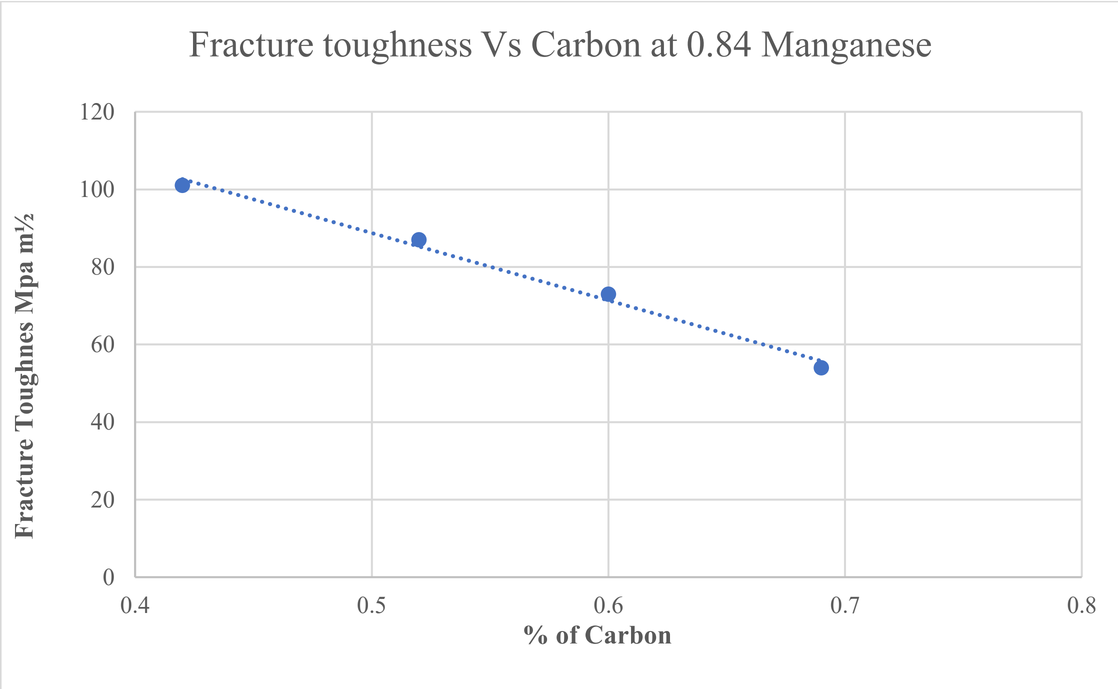


Figure 9. Fracture toughness vs Carbon at 0.84 Manganese [12]

Comparing the two graphs where carbon content is the same, but in the second graph, fracture toughness is low because of low manganese presence. When the Mn/c ratio decreases, the fracture toughness also decreases [12].

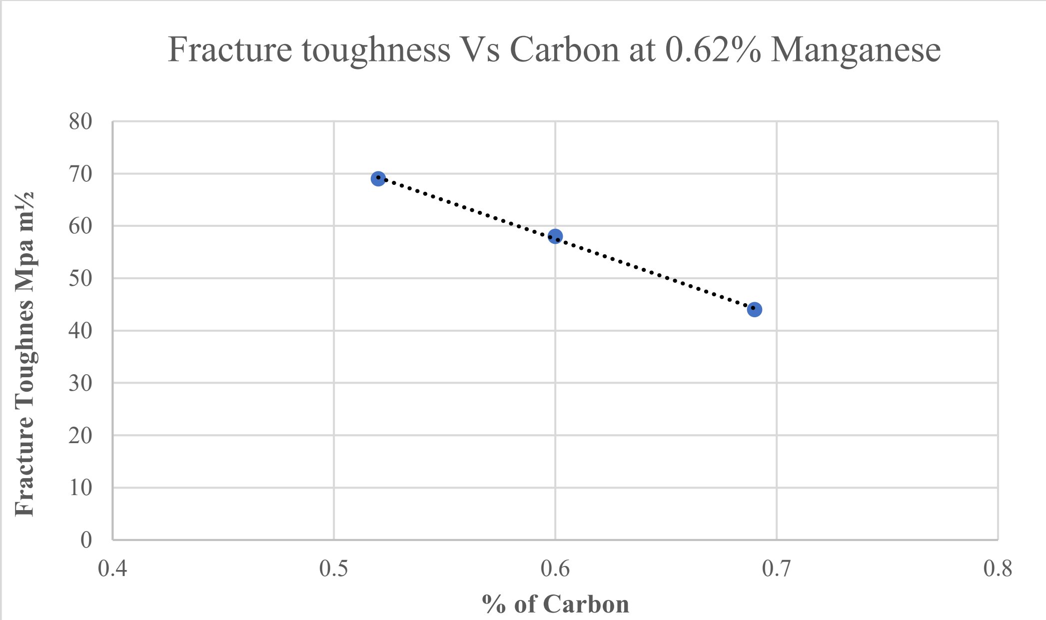


Figure 10. Fracture toughness vs Carbon at 0.62% Manganese [12].

From the graph, we can say that increasing the carbon percentage increases cementite lamellas. In short, it increases the carbide, which has 6.67% carbon. Which provides the hardness and strength but at the same time affect negatively on the fracture toughness.

Dilution Factor - In Pearlite, the dilution factor is a necessary term. Dilution factors: The Dilution factor's value is at the eutectoid steel is 1, and more than 1 for hypo-eutectoid. When the carbon percentage increases, cementite lamellas' thickness also increases, which negatively affects the impact energy and fracture toughness.

The thickness of Cementite Lamellae (t) = $0.15 \times St \times Cs$

St = True interlamellar distance

Cs = Carbon content in steel

Dilution factor = $\frac{0.8 \times Vp}{Cs}$

Vp = volume fraction of Pearlite.

Silicon

Silicon is a ferrite stabilizer and has a minor influence on material strength by solid solution hardening. Having a negligible solubility in cementite, silicon has proven to inhibit cementite growth or precipitation and stabilizes Pearlite at exposure to high temperatures. Thus, silicon helps to improve thermal stability and high-temperature strength. While also improving wear resistance, too high alloying content may have an embrittlement effect and negative influence on impact properties. Silicon in the steel making process is used as a deoxidant to reduce oxygen and prohibits iron oxide inclusions.

Manganese

Manganese enhances the impurities such as lead, phosphorus, tin, segregation on the grain boundary. Manganese can dissolve in cementite so that it will help to alloy in cementite formation. Manganese is an essential desulfurize and deoxidizer. It has less segregation tendency. Manganese favourably affects forge ability and weldability.

Phosphorus

Phosphorus has a high tendency of segregation at grain boundary during solidification. Phosphorus dissolves in ferrite, which increases Strength. As the amount of phosphorus decreases, the ductility and impact toughness also decrease, not suitable for wheels.

Sulphur

Sulphur also has a high tendency to segregate at grain boundaries. Sulphur has a detrimental effect on transverse ductility, notch impact toughness, weldability, and surface quality. So, steel should have less quantity of sulphur. However, sulphur in the range of 0.08 –0.33% is intentionally added to free-machining steels for increased machinability.

Chromium

Chromium (Cr) is a medium carbide former. In the low Cr/C ratio range, only alloyed cementite (Fe, Cr)3C forms. Chromium increases the hardenability, corrosion and oxidation resistance of steels. Cr in steels' addition enhances the impurities, such as P, Sn, Sb, and As, segregating to grain boundaries and induces temper embrittlement. Chromium carbides are hard and wear-resistant and increase edge-holding quality.

Nickel

Produces more excellent hardenability, impact toughness, and fatigue resistance in steels Nickel dissolving in ferrite improves toughness, decreases FATT50% (^{0}C), even at sub-zero temperatures. Nickel has 0.30% in R7T steel.

Molybdenum

Carbide former and with other alloy element molybdenum, it increases hardenability and high temperature creep strength.

Vanadium

Vanadium may be added to reduce excessive grain growth during heat treatments and thus promote a fine-grained microstructure.

Chromium and Vanadium improve wear resistance by the formation of stable carbides and enhance strength and toughness. Residual alloying elements primarily control and optimize the manufacturing process, improve cleanliness, grain refinement, and carbide formation.

Their usage and amount may differ between different steelmakers, but they usually are limited and specified in discrete intervals for each wheel grade specification to avoid unexpected material behaviour.

4. Microstructure

The microstructure of steel has a strong influence on the fracture toughness (K_{1C}) of medium carbon steel. The fracture toughness of the as-received steel found to be higher than the annealed steel for the same notch depth and notch angle [13].

4.1 Hypo-eutectoid

When steel alloys carbon has less than the 0.8%, The ferrite ratio to cementite is 87:13 by weight, where ferrite contains 0.08% carbon. In comparison, cementite contains 6.67% carbon, making it brittle and hard. The alternate nucleation and growth of cementite and ferrite considered. The first cementite formed thickens so that the adjacent austenite becomes impoverished in Carbon. The increasingly reduced carbon content of the adjacent austenite ultimately permits the nucleation of a layer of ferrite. The ferrite thickens while both layers grow edgewise, and as the adjacent austenite becomes impoverished in ferrite, another cementite layer nucleates.

R7T is medium carbon steel with a hypo-eutectoid microstructure that contains the 5 % to 10% volume fraction of ferrite and remains perlite. Pearlite is vital in the microstructure. Pearlite is alternating lamellas because of its behaviour and volume fraction in the microstructure. Pearlite's interlamellar spacing plays an important role when the interlamellar spacing between two cementite lamellas increases, decreasing the yield strength. When the interlamellar spacing decreases, the yield strength increasing. Total strength in hypo eutectoid is the sum of pro-eutectoid ferrite and pearlite strength [14].

4.2 Fracture toughness and microstructure

Primarily fracture toughness depends on the three main factors in the hypo-eutectoid microstructure.

4.2.1 Pro- eutectoid ferrite

The volume fraction of ferrite is an essential factor for fracture toughness. Because of the availability of slip bands in equiaxed ferrite has a tendency propagation of the crack. The formation of ferrite and volume fraction of ferrite depends on the cooling rate and heat treatment. That is why the propagation of crack easily propagates in the equiaxed ferrite, while if the ferrite is finer, the crack will not propagate easily as per the Hall-Petch strength and the growth of ferrite is depends on the cooling rate. If steel with annealing process the ferrite gets too much time for the growth and pro-eutectoid became an equiaxed grain which is not suitable for the fracture toughness.

4.2.2 Pearlite

There is no relation between the pearlite spacing and the prior austenite grain size. However, pearlite lamella spacing has an essential role in the manner of fracture toughness. If the lamellar spacing is less, the strength will increase, and it will oppose the crack propagation, which increases fracture toughness. The lamellar spacing of Pearlite is not dependent on the grain size but depends on the cooling rate. If the cooling rate is very low, the lamellar spacing of Pearlite is more, and Pearlite becomes coarse. Because when the grain size is significant, the number of nucleation sites is less because grain boundaries are less.

4.2.3 Pearlite colonies

Pearlite colonies are nothing but the no of pearlite sites with different orientations of perlites. Because the different orientation of Pearlite increases the strength and prevents the propagation of the crack, in short, it shows a positive effect in the view of fracture toughness for a specific limit.

For Ferrite

$$\sigma_y^\alpha = \sigma_j + \frac{\sigma_k^\alpha}{\sqrt{d_\alpha}} \tag{4.1}$$

where σ_j = fraction stress

σ_k^α = Hall-Petch constant

d_α = grain size of ferrite

For Pearlite

$$\sigma_y^p = \sigma_j + \frac{\sigma_k^p}{\sqrt{d_p}} \tag{4.2}$$

σ_k^p = Hall patch constant for the Pearlite

d_p = mean free distance.

Total Yield strength =

$$\sigma_y = \sigma_y^p + \sigma_y^\alpha \tag{4.3}$$

They have different Hall patch constant. Hall patch constant for a ferrite is 1.13* $V_\alpha^{o.33}$ and for Pearlite is 0.25* $V_\alpha^{o.33}$. When it exceeds the value, the impact toughness and fracture toughness degrade.

As we know, fracture toughness calculated by equation no 3

$$K_{Ic} = F\sigma_f\sqrt{\pi a} \tag{4.5}$$

$K_{Ic} = Fracture\ toughness$

F = geometric function

σ_f= applied stress failure

a = crack length

and for propagating crack stress should be greater than applied stress at the crack tip, which depends on the bonding, surface energy γ_p, carbide thickness C_o, young Modulus E and v poison's ratio as per

$$\sigma_f > \frac{4E\gamma p}{\pi(1-v^2)Co} \tag{4.6}$$

And surface energy, which is a barrier for propagating the crack, is directly proportional to the volume fraction of ferrite. So, we found that increasing the volume fraction of ferrite will improve the fracture toughness [14].

$$\gamma_p \propto \mathrm{V} \tag{4.7}$$

4.3 Grain size

The nucleation of perlite at grain Boundary of austenite grain. The strength of pearlite microstructure mainly depends on the interlamellar spacing of cementite lamella, and this interlamellar spacing is not an important function of grain size. Still, the interlamellar spacing depends on transformation temperature and cooling rate.

When lamellas of cementite and ferrite are parallel, the Pearlite is known as colonies. Moreover, a group of various colonies which has different orientation is known as nodular. The size of nodular depends on austenite grain size. If Austenite grain size is large, then the nodular are big.

When the Austenitizing temperature is high, the carbides particles become coarsen and dissolve in it. The particle distribution can no longer prevent migrating grain boundaries and forms the grains with big size.

When the grain size of austenite is large, then the grain boundaries are also less, and because of its lots of colonies nucleate. Still, they are nucleating from the same parent, so they have less misorientation, and in the resulting, the boundaries are not sufficient mismatched. While the small size of austenite grain size has more boundaries so more nucleation site, so colonies have more misorientation and resulting in a mismatch the boundaries

Toughness in medium carbon steel does not only depend on the ferrite but also on pearlite colonies. Pearlite colonies with different orientations are unfavourable to propagate crack and travel dislocations within it, and this property provides excellent toughness.[15]

That means good toughness with sufficient strength; the austenitizing temperature should below get austenite small grain size, which will improve good impact and fracture toughness.

4.3.1 Grain size effects on the mechanical properties

1) As grain size increases, the yield strength decreases while tensile ductility increases at the fracture.

2) The fracture toughness value highest at the coarse grain, where tensile stress and fracture stress are lower.

4.3.2 Interlamellar distance on Fracture toughness other fracture properties

1) Yield strength, fracture strength and tensile stress increases concerning decrease to an interlamellar distance

2) Fracture toughness (K_{IC}) is a little bit complex. Fracture toughness has the lowest value, at about 30 μm interlamellar distance. When interspace lamellas distance equals 25μm, Fracture toughness (K_{IC}) at high value and beyond it again, Fracture toughness (KIC) decreases [14].

5. Experimental techniques

5.1 Fracture toughness method

The fracture toughness is a material property that opposes them or produced resistance to failure after defecting or cracking. Because of various factors or defects, cracks initiate or form where Fracture toughness resists the crack propagation of that initiated crack fracture toughness denoted by K_{IC}.

Fracture toughness is nothing but a critical stress intensity factor where crack start to propagate.

It has three Modes of stress intensities.

$$K_I = \sigma\left((2\pi r)^{1/2}\right) \qquad \text{Mode (1)}$$

$$K_{III} = \tau\left((2\pi r)^{1/2}\right) \qquad \text{Mode (2)}$$

$$K_{II} = \tau\left((2\pi r)^{1/2}\right) \qquad \text{Mode (3)}$$

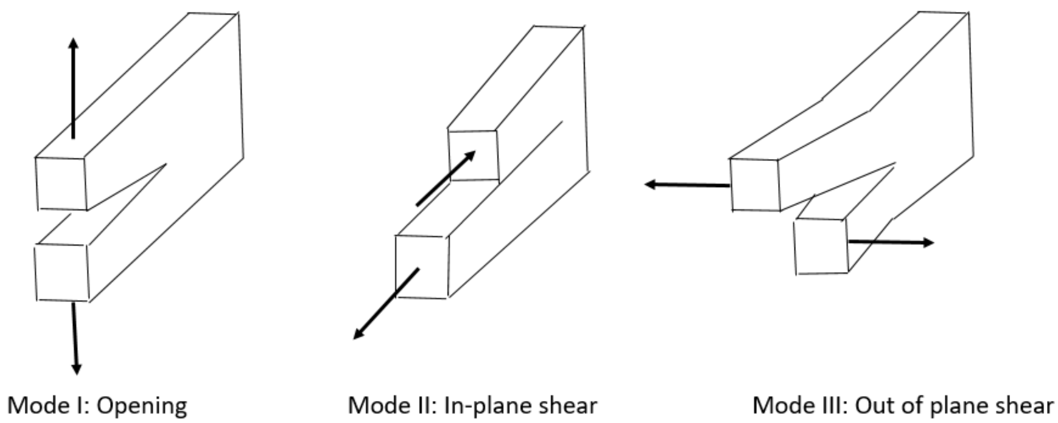


Figure 11. Three modes of fracture toughness

For compact tension test plane-strain fracture toughness, K_{IC} [FL-3/2]—the crack-extension resistance under conditions of crack-tip plane strain in Mode I.

Fracture mechanics has three types of failure mechanisms.

1) Linear Elastic fracture Mechanics (Linear – Time independent)

2) Elastic and plastic fracture mechanics (Nonlinear – Time independent)

3) Elastic and plastic fracture mechanics (Time-Dependent – Dynamic, Viscoelastic, Viscoelastic fracture mechanic).

We conduct the standard fracture toughness testing method as ASTM E399, which is used to measure the material's fracture toughness. This method is used for the linear elastic plan strain fracture of a metallic material as per the standard. The value of K_{Ic} is calculated from this force using equations that have been established by elastic stress analysis of the specimen configurations specified in this test method.

Metallurgical variables such as composition or heat treatment, fabricating operations such as welding or forming effects on the fracture toughness of new or existing materials. This method is used to find K_{Ic} values in relation to a particular application should signify that a fracture control study has been conducted for the component with regard to the expected loading and environment and concerning the sensitivity and reliability of the crack detection procedures that are to be applied prior to service and subsequently during the anticipated life.

In the ASTM E399, we can get three types of failure behaviour load-displacement curve as below

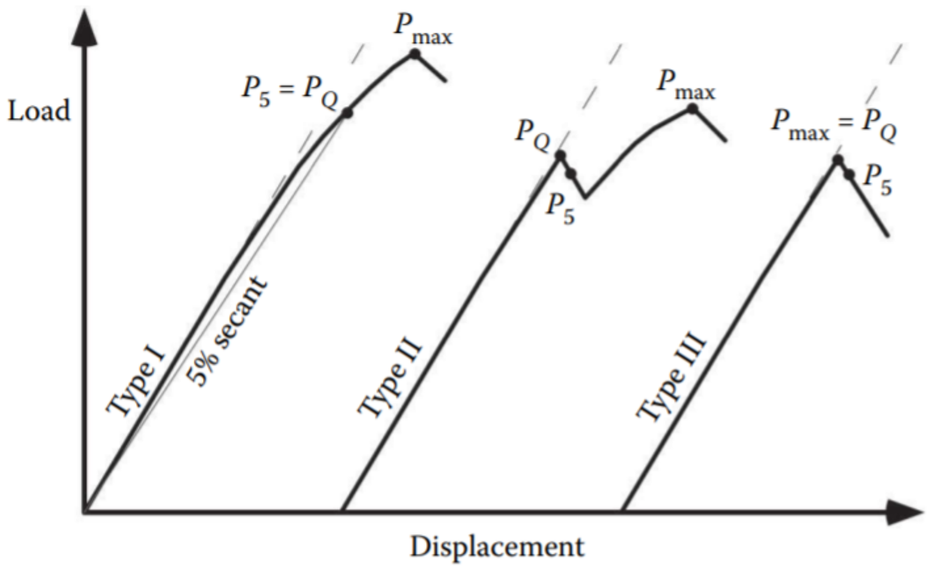


Figure 12. Load vs Displacement [14]

Type 1- Type I behaviour, the load-displacement curve is smooth, and it deviates slightly from linearity before reaching a maximum load, Pmax. This non-linearity can be caused by plasticity, subcritical crack growth, or both. For a Type, I curve, PQ = P5.

Type 2 - Type II curve, a small amount of unstable crack growth (i.e., a pop-in) occurs before the curve deviates from linearity by 5%.

Type 3 - Exhibit behaviour fails before achieving 5% non-linearity. In such cases, P_Q = Pmax.

5.2 Preparation for testing

5.2.1 Pre-fatigue crack

The validity of K_{Ic} value depends on the value determined by this test method depends upon establishing a sharp-crack condition at the tip of the fatigue crack to ensure predominantly linear-elastic, plane-strain conditions. To establish the appropriate crack-tip state, he stresses Intensity factor level at which specimen fatigue pre-cracking is conducted is limited to a relatively low value. For that, we used to perform the fatigue crack, and we use the fatigue pre-cracking machine. Careful alignment of the specimen and fixturing is necessary to encourage straight fatigue cracks. The fixturing shall be such that the stress distribution is uniform across the specimen thickness and symmetrical about the plane of the prospective crack.

5.2.2 Specimen size and preparation

The preparation of the sample and select the size of the specimen is an essential step because the width of the specimen influences the readings and results of the test. After casting and metallurgy, the machining operation is done to acquire the shape, size, and tolerance size value.

- Crack size (a) should be nominally between 0.45 and 0.55 times the width (W).
- It is recommended that the thickness (B) is nominally one-half the specimen width(W).
- We can form three types of pre-crack notches, Three fatigue crack.
- Starter notch configurations are shown in Figure 10. To provide fatigue pre-cracking at low-stress intensity levels, by the easy way, we can go with the suggestion of root radius for a straight-through slot terminating in a V-notch is 0.08 mm (0.003 in.) or less. For the chevron form of the notch, the suggested root radius is 0.25 mm (0.010 in.) or less. For the slot ending in a drilled hole,

it is necessary to provide a sharp stress raiser at the end of the hole that this stress raiser is so located that the crack plane of the fatigue pre-crack and subsequent 2 % crack extension shall be parallel to the plane of the starter notch to ±10°.

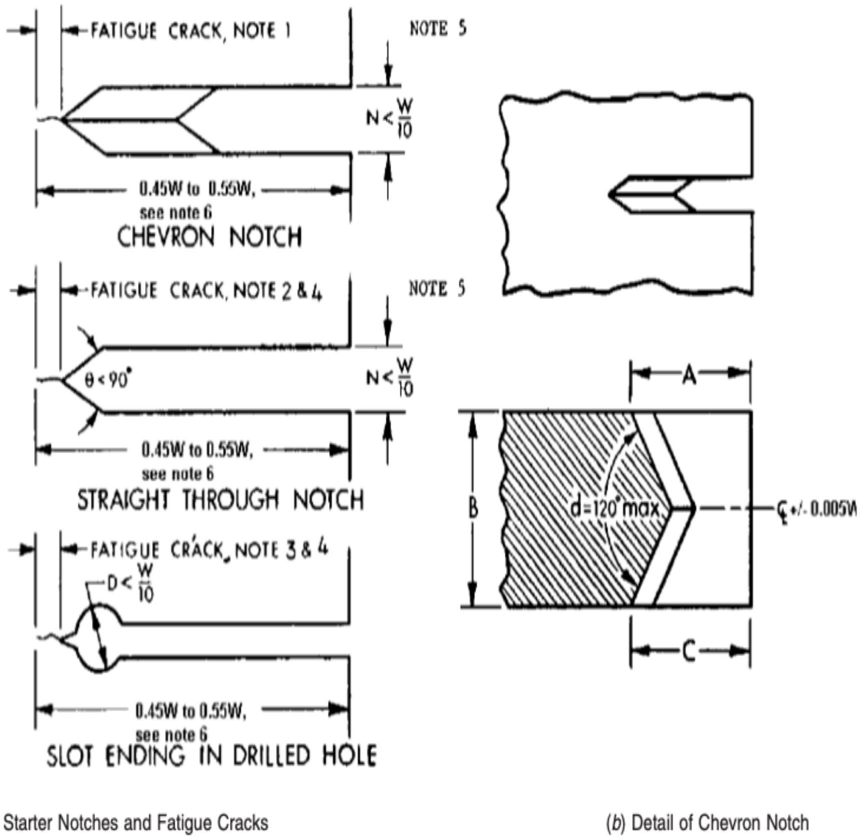


Figure 10. Terminology and details about pre-crack design and details [5]

- The size of the fatigue crack on each face of the specimen shall not be less than the larger of 0.025W or 1.3 mm for the straight-through crack starter configuration, not less than the larger of 0.5D or 1.3 mm for the slot ending in a hole of diameter D < W/10 and need only emerge from the chevron starter configuration.

5.2.3 Set up for testing

We perform the test as per the ASTM E99 Standards, and we are using the displacement gauge to measure the crack spanning while load applying. The displacement gauge has two cantilever clips. It should be giving enough clearance to adjust or spin in the notch area to take correct inputs with them. The displacement gage electrical output represents relative displacement (V) of two precisely located gage positions spanning the crack starter notch mouth.

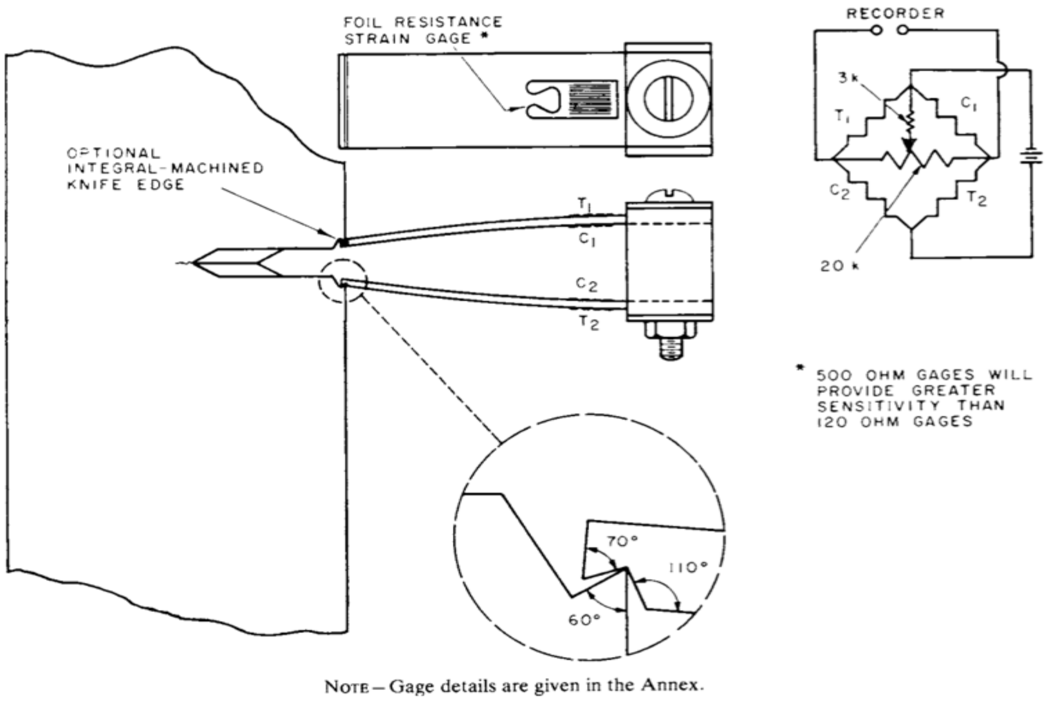


Figure 11. Double cantilever displacement gauge terminology with Showing Mounting through Integral Knife Edges [5].

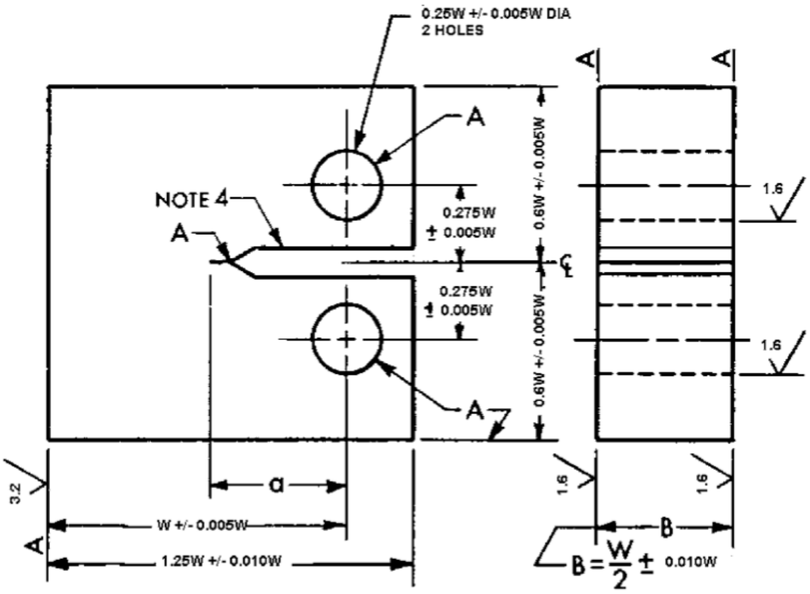
5.3 Testing method requirement

There are requirements to assure a correct KIC value from a test. These are all described in ASTM E399. Some of the requirements are regarding the test's procedure, and as one of these in the studied set of tests, broke these will not be described here. Others consider the length of the fatigue crack and the size of the cyclic load applied during the pre-fatigue cracking. Other requirements are to ensure the correct geometry of the specimen. These are clearly explained in ASTM E399 and not broken in the studied tests, so these will also not be described further. The requirements are broken in the examined tests related to excessive plasticity and Pmax/PQ ratio. For calculating fracture toughness, the following three conditions should be qualified, and then the measured fracture toughness is valid.

$$0.45 \le a/W \le 0.55 \qquad \text{(Term 1)}$$

$$W - a \geq 2.5 \left(\frac{K_Q}{\sigma ys}\right)^2 \qquad \text{(Term 2)}$$

$$P_{max} \leq 1.10\, P_Q \qquad \text{(Term 3)}$$



NOTE 1—Surface finishes in µm.
NOTE 2—*A* surfaces shall be perpendicular and parallel to within 0.002 *W* TIR.
NOTE 3—The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen within 0.005 *W*.
NOTE 4—Integral or attachable knife edges for clip gage attachment to the crack mouth may be used (see Figs. 3 and 4).
NOTE 5—For starter notch and fatigue crack configuration see Fig. 5.
NOTE 6—1.6 µm = 63 µin., 3.2 µm = 125 µin.

Figure 12. Compact test specimen size and proportion [5].

5.3.1 Fracture toughness Calculations.

To find K_{IC}, we have to find K_Q after validation of test by terms which are mentioned before in requirements

$$K_Q = \frac{P_Q}{\sqrt{B * B_N}\sqrt{W}} \cdot f\left(\frac{a}{W}\right)$$

Where PQ = force

B = specimen thickness

B_N = specimen thickness between the roots of the side grooves

W = specimen width (depth)

a = crack size

f(a/W) = geometrical function.

Where,

$$f\left(\frac{a}{W}\right) = \frac{\left(2+\frac{a}{W}\right)\left[0.886+4.46\left(\frac{a}{W}\right)-3.32\left(\frac{a}{W}\right)^2+14.72\left(\frac{a}{W}\right)^3-5.6\left(\frac{a}{W}\right)^4\right]}{\left(1-\frac{a}{W}\right)^{\frac{3}{2}}}$$

5.3.2 Crack Opening displacement compliance (V_m/P)

We can calculate the crack opening displacement compliance by crack measurement denoted by V_m/P.

$$\frac{V_m}{P} = \frac{1}{E'}\frac{1}{B_e}\, q\, \frac{a}{W}$$

$$q\left(\frac{a}{W}\right)= \frac{19.75}{\left(1-\frac{a}{W}\right)^2}\left[\left[0.5 + 0.192\left(\frac{a}{W}\right) + 1.385\left(\frac{a}{W}\right)^2 + 2.9192\left(\frac{a}{W}\right)^3 - 1.842\left(\frac{a}{W}\right)^4\right]\right]$$

Where V_m is crack mouth opening displacement,

E' = (1-v) E where E is Young’s modulus and v is Poisson's ratio.

Be = B-(B-B_N)^2/B.

The calculation for crack measurement

$\frac{a}{W}$ = 1.0002- 4.500*U + 113.157·U^2 - 172.551·U^3 - 1879.944·U^4 - 1514.671·U^5.

Where $U = \frac{1}{1+\sqrt{\frac{E' B_e V_m}{P}}}$ P = applied force

5.4 Microstructure evolution

The ability to set relations between microstructure and material properties like fracture toughness is essential for obtaining a universal profound deep knowledge and an accurate prediction of properties. However, the nature of the imaging analysis process for microstructural evaluation may give errors that can influence the results even for large sample sizes. Consequently, the actual material behaviour and composition in some cases may be unattainable solely by image analysis. Mechanical testing often gives a superior global averaging of mechanical properties.

Microstructural characteristics of grain size, phase fractions, morphology, and fracture surfaces were analyzed using standard metallographic techniques with a light optical microscope. For microscopy, metallographic preparation by SiC grinding, polishing and etching were used in general. In the last polishing step, chemo-mechanical polishing with SiO2 (colloidal silica) was used instead of traditional abrasive diamond polishing. Using mechanical chemo polishing, the quality of prepared surfaces improved, which allowed for a more accurate evaluation of the cementite lamella morphology in Pearlite. To reveal the microstructure, etching was performed with Nital solution.

5.5 Test results

Table 4. Experimental results

Material - Sample No.	**UTS [MPa]**	**YS [MPa]**	**K_Q [MPa.m$^{1/2}$]**	**Material – Sample No.**	**UTS [MPa]**	**YS [MPa]**	**K_Q [MPa.m$^{1/2}$]**
R7T-1	893	576	92.0925	R7T-10	882	546	82.780
R7T-2	881	564	91.45167	R7T-11	596	587	94.870
R7T-3	906	565	90.15	R7T-12	914	601	94.868
R7T-4	875	538	82.10333	R7T-13	900	586	87.935
R7T-5	892	573	86.152	R7T-14	878	546	91.598
R7T-6	883	576	96.99167	R7T-15	899	573	91.538
R7T-7	892	586	90.61667	R7T-16	843	535	87.983
R7T-8	891	574	96.535	R7T-17	915	583	95.618
R7T-9	867	553	92.188	R7T-18	887	567	86.770
R7T-10	873	572	91.173	R7T-19	869	550	89.370

6. Discussion

An excellent way to trace the quality of a material is that put the yield strength together with toughness. The fracture toughness of ER7 enhanced with time. The obtained results demonstrate that the capacity to measure the fracture toughness of materials and a proper collection of the related metallurgical parameters help develop the manufacturing process of the wheels.

The mechanical properties of medium carbon steel which has hypereutectoid Pearlite and depend on the following three factors

1. The ferrite and pearlite percentage

2. The interlamellar spacing of the Pearlite

3. Nodule diameter of the Pearlite6.1 Yield strength

From the testing, we can see that the fracture toughness decreases but again increases concerning the yield strength at the beginning. Yield strength increases with decreasing the interlamellar space of Pearlite.

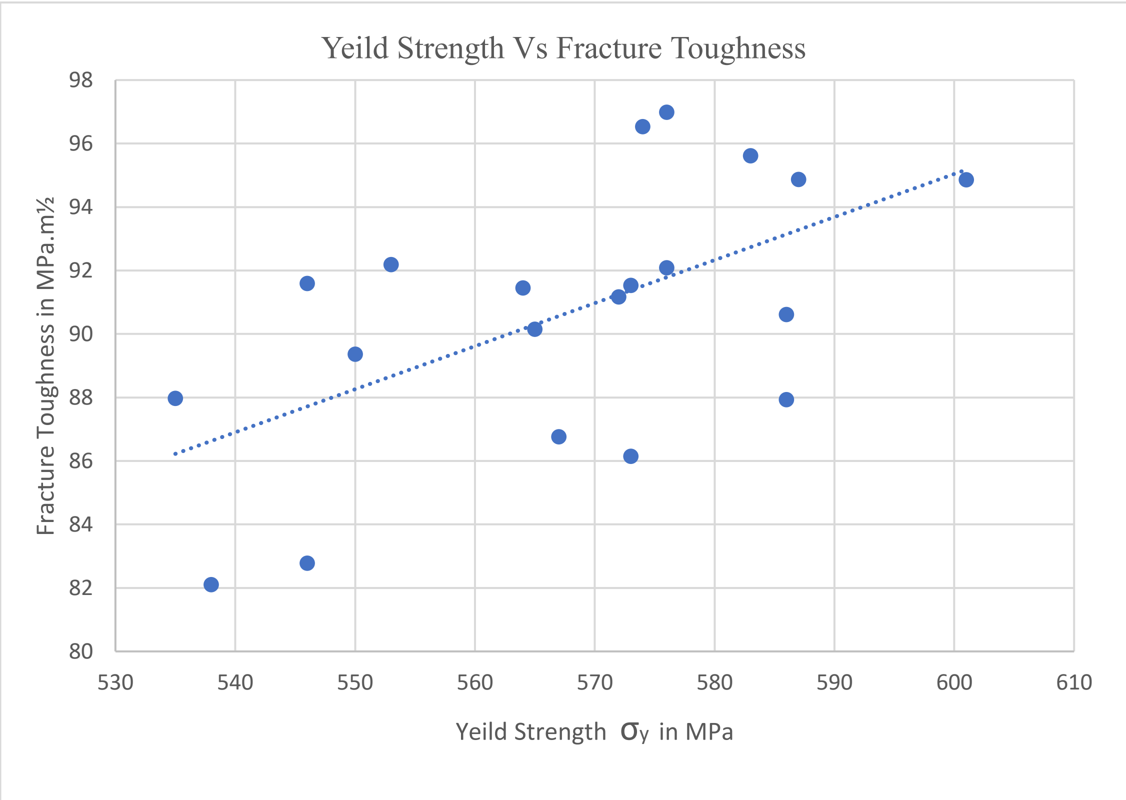


Figure 13. Fracture toughness vs Yield strength from the tests.

We see that the deviation of yield strength is 17.43696 for fracture toughness results; yield strength is an important parameter related to fracture toughness. Another possibility is that when refining the grain obviously as per the hall patch, the yield strength will increase because the number of grain boundaries and nucleation sites for lamellas increased simultaneously during grain refining. Ferrite will saturate along the prior austenite grain boundaries in a small section, and as we know, the ferrite has less hardness.

Ferrite is soft and ductile. It provides toughness because of propagation of crack with plasticity region, so as Fracture toughness is increased with increasing the strength. Yield strength depends on the interlamellar spacing. Interlamellar spacing depends on the Carbon content, and transformation temperature, cooling rate [15].

Product Index = yield strength **X** Fracture index.

In the production of R7T steel, the parameter production index is an essential parameter that is decided by yield strength and fracture toughness [6].

6.2 Tensile strength

Medium carbon steels containing a mixture of pro eutectoid ferrite and Pearlite, the ferrite tends to influence the strength of the steels mainly when present as a continuous grain boundary network. When such steels contain small amounts of discontinuous ferrite, it appears that the pearlite interlamellar spacing is the dominant microstructural parameter controlling the strength. We can see from the results that for the same fracture toughness results, the deviation of Tensile strength is 65.3826. it shows the importance of the relation of Tensile strength to fracture toughness.

Grain size also affects the tensile strength as yield strength (the hall patch rule). When grain size increases, the Tensile strength decreases, and when grain size decreases, the strength increases [16].

When grain size increases, it affects the pearlite nodule's size but not affects pearlite colonies. When grain size is increased, then pearlite nodule also increases. Tensile strength also shows the same effect, but when austenite grains are very coarse, the Pearlite nodule also becomes coarse. It enhances the fracture toughness by Coarse nodule opposing the propagation crack with the help of coarse perlite nodule [17].

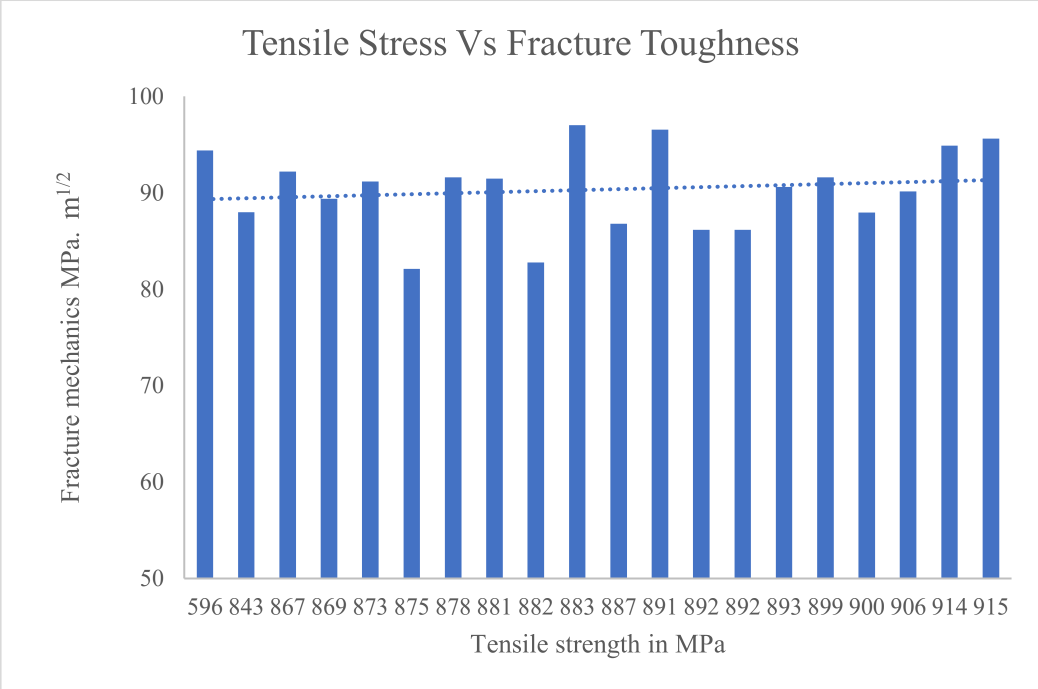


Figure 14. Tensile strength vs Fracture toughness

Tensile strength is also mainly dependent on the interlamellar spacing. When interlamellar spacing distance is low, the tensile strength at a peak. When the interlamellar spacing distance increases, then Tensile strength is decreasing. While the interlamellar spacing distance is more refined, then first decreasing the fracture toughness after that, it will increase. When the Pearlite is coarser, the interlamellar spacing distance is large; due to that, the volume fraction of ferrite mean free distance will increase as the fracture toughness starts to decrease.

6.3 Microstructure

As we see, R7T is in the medium carbon steel category. It contains 0.52 % carbon, so after quenching followed by tempering, it has a hypo- eutectoid microstructure with 5%- 10% pro eutectoid with Pearlite. In Figure 15, we can see the dark section shows the perlite section while the white area shows the pro eutectoid ferrite section in microstructure in Secondary electronic microscopy.

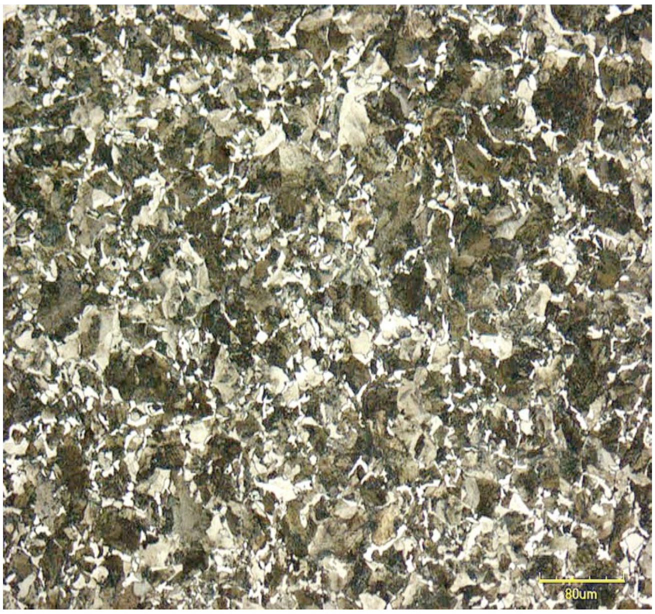


Figure 15. Microstructure of R7T steel with Light microscopy.

If microstructure contains 7% or less than 7% pro eutectoid ferrite in hypo eutectoid, Pearlite plays an essential role in studying microstructure concerning mechanical properties.

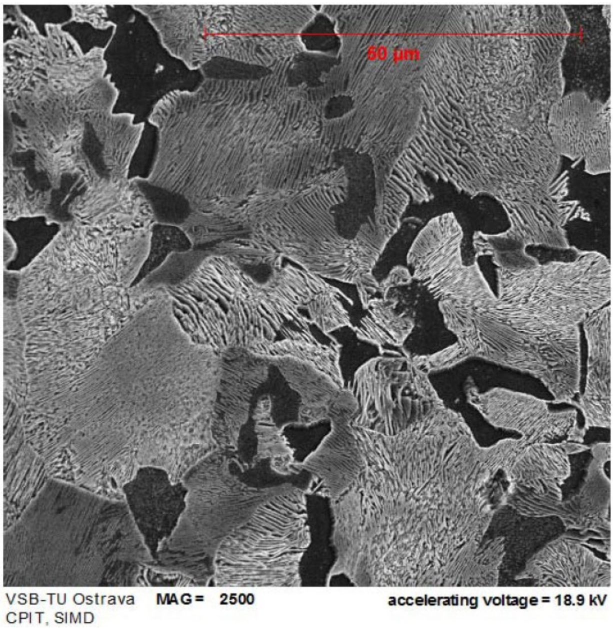


Figure 16. SEM – Microstructure of R7T with details of Perlite section

7. Conclusion

1. Fracture toughness is an important material property that the mechanical properties can influence.
2. Yield strength has a positive impact on fracture toughness within limits.
3. As yield strength increase, the Fracture toughness also increases.
4. Pearlite has played a vital role in strength and fracture toughness in the microstructure.
5. Yield strength has more impacted on fracture toughness than Tensile strength.
6. The grain size of prior austenite grain is an essential factor. Finned and uniformed grain size provides good strength as per Hall-Petch criteria and so Fracture toughness too.
7. Pearlite colonies are independent of grain size; However, the Pearlite nodule depends on the grain size. When the grains were more or extreme coarse, the pearlite nodule also, and in such a situation, it plays a negative role and decreases fracture toughness.
8. If Interlamellar spacing distance is low, then the microstructure provides good yield strength and vice versa.
9. Interstellar spacing distance depends on the transition temperature, cooling rate, and Carbon content, not on the austenite grain size.
10. If the mean free ferrite distance is more, the strength will decrease.
11. We found a pro eutectoid ferrite presence at the grain boundaries with the fine structure from microstructure evaluation, which increases the strength and fracture toughness. We can see in the microstructure crack is attested in the Pearlite structure.
12. Where if equiaxed grains are formed, they are ductile, and as a result, strength decreases.
13. The effect on fracture toughness by yield strength more intensive than Tensile strength.
14. The effect of Carbon is negative. When carbon percentage increasing the fracture toughness is decreasing. However, the percentage of Manganese increases the fracture toughness will improve.
15. If Manganese /Carbon ratio increase, the fracture toughness will improve.

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